SPACE SHUTTLE MAIN ENGINE TURBOPUMP TRANSDUCER

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Introduction:

Part of the credit for the success of America's Space Shuttle goes to the operation of the Rocketdyne-built Space Shuttle Main Engines (SSME). Three Main Engines along with the Solid Rocket Boosters, have powered the Space Shuttle's Columbia and Challenger to orbit several times; with more to come. (Figure 1) The reusability of the SSME has been demonstrated by the success of the first five flights of the Columbia using the same three SSMEs.

Space Shuttle Main Engines (SSME)

Advances in liquid rocket engine technology were required to meet the life and reusability criteria set by the Space Shuttle Program for the ~~SSME~~. To verify the SSME design life, extensive development testing and hardware inspection was required.

Each SSME has four turbopumps which are used to pump propellant for combustion. One of these turbopumps which pumps liquid oxygen is the High Pressure Oxygen Turbopump (HPOTP). Using a two-stage turbine, the HPOTP produces 29,410 horsepower to pump 69.6 pounds per second of liquid oxygen. (Figure 2) One area of hardware inspection and testing to insure engine life and operation was in the area of the rocket engine turbopump bearings. Bearing life is critical to the overall reusability of the HPOTP.

After each development test of the SSME, inspection of many engine parts are made. During inspection of the HPOTP it was observed that some of the bearings in the pump were wearing excessively. The bearings in question were the number 3 and 4 bearings in the pump. (Figure 3) To determine the cause of the wear, one HPOTP would be instrumented to monitor the bearing conditions.

Transducer Design Considerations:

Before the HPOTP could be instrumented, a means to monitor the bearing load conditions was devised. Considerations were made with respect to the operating conditions of the HPOTP and the type and placement of the instrumentation.

The regions around the bearings and the bearings themselves are cooled with liquid and gaseous oxygen. The temperature ranges from ambient to -273°F. The area is pressurized up to 400 psig during the HPOTP operation. Because of the Liquid Oxygen (LOX) environment, all instrumentation placed in the pump would have to be compatible with LOX or be covered to protect it from the LOX.

A protective coating was proposed that would cover the instrumentation to protect it from the LOX environment. The coating, supplied by Raybestos-Manhattan called Refset, was used to cover non-LOX compatible materials. Raybestos-Manhattan recommended the Refset compound as the most suitable for a pressurized LOX environment. Further laboratory tests by Rocketdyne verified the use of Refset in the HPOTP. The tests included LOX impact, thermal shock and strain transfer tests.

The LOX impact test verified the impact resistance of Refset in a pressurized LOX environment. The test impacted a sample of Refset with 72 ft-lbs of energy. The environment around the sample was controlled to -220°F and pressurized to 600 psig. Twenty impacts were made without a Refset reaction.

The thermal shock test determined the thermal sensitivity of Refset. A test bar coated with Refset was submerged in liquid nitrogen. Strains up to 6000 micro in./in. were then applied to the Refset area of the Test bar. The test was repeated four times. After the tests, the Refset coating was examined for cracks or loss of adhesiveness. No visual or microscopic indications of cracking, peeling or any other evidence of loss of adhesion was found.

The strain transfer test verified the use of Refset with strain gages. A test bar was straingaged and placed in a tensile test machine. Strains were recorded as load was applied with and without a Refset coating over the strain gages. The test data showed no difference in recorded in strain between the uncoated and coated strain gages. It was concluded from these tests that Refset would be acceptable as a protective coating over non-Lox compatible instrumentation.

The type and placement of the instrumentation in the HPOTP was the next consideration. Several methods were reviewed to monitor the load on the bearing in the HPOTP. Figure 4 shows the use of a small load cell (piezioelectric type) to measure loads applied to the bearings. As shown in Figure 3, the cartridge support is attached to the HPOTP housing and the bearing cartridge acts as a spring to allow the HPOTP to travel axially. The axial movement is plus and minus forty thousandths of an inch from the zero position. One of the axial travel stops is the cartridge support. The other stop is a HPOTP part that hooks over the edge of the bearing cartridge. The load cell would be placed on the cartridge support to measure the load as the bearing cartridge bottoms while traveling toward the Turbine End. Advantages to the loadcell method would be that the load cell could be calibrated independent of the pump and the loadcell could be matched to the estimated bearing load. By selecting the proper loadcell range, the signal output could be optimized. The disadvantages of the loadcell are that load measured is in only one direction and the little availability of the loadcell with the proper range and size from a supplier.

The next two methods were derivatives of the loadcell idea. (Figures 5 and 6) Each used a load column to sense the bearing load. Both methods removed the doubt of loadcell availability. The loadcell would be manufactured "in house" but the load measured was still only in one direction. The design and installation of the load columns also was complex with anti-rotation tangs and retainer rings.

The next method (Figure 7) uses the cartridge support as a spring element. Stress concentration holes were devised to try to increase the strain output but with little success. Less than 0.025 mV/V output was calculated using the estimated bearing loads. Because of the low signal output and the one direction load, this method was not used. The last two methods that were reviewed incorporated the use of the Bearing Cartridge as the spring element. Figure 8 shows a strain gage easily placed on the pump end of the Bearing Cartridge. This location would sense applied bearing loads in both directions and would require minimum rework of the HPOTP hardware. The disadvantage was the questionable low signal output.

Figure 9 is similar and requires little hardware modification but some doubt as to the signal output.

After studying the last two methods it was observed that during bearing loading the strains in the Bearing Cartridge of the last two proposed locations were opposite in direction. That is, as the load was applied toward the turbine end of the HPOTP, the strain gage location in Figure 8 would be in compression and the strain gage location in Figure 9 would be in tension. By using the two locations and wiring them in the same Wheatstone instrumentations bridge, an additive output could be gained. This additive signal output would overcome the concern of low output from only one location.

To verify the signal output of the last two methods, a bench test was made using the Bearing Cartridge. Strain gages were installed on the Bearing Cartridge in the two designated locations. The Bearing Cartridge, mounted in fixtures to simulate the HPOTP, was loaded up to 3000 pounds in both axial directions. Strains up to 1200 μin./in. were records from the individual locations.

As the bearing load strain gage locations were being specified, a secondary objective of monitoring HPOTP shaft axial travel was suggested. By knowing the location of the shaft axially in the HPOTP, it would verify the direction of the bearing load and provide information on the HPOTP operation. The slotted area of the Bearing Cartridge became an ideal area for the strain gages to monitor shaft axial movement.

The layout of the two channels of shaft travel monitoring strain gages (Bridges No. 2 and No. 5) and the three channels of load monitoring strain gages (Bridges No. 1, No. 3 and No. 4) are shown in Figure 10. The Bearing Cartridge was modified slightly to allow for easier wire routing of the load monitoring strain gages.

Strain gages were used as the monitor sensor for several reasons. The installation of the strain gage required very little hardware modification.

Also, Rocketdyne was familiar with strain gage installations and the accompanying instrumentation.

The next step in the design considerations to monitor bearing load and shaft travel was to specify the type of strain gages and epoxy to use. The first consideration would be the environment where the strain gage would operate and the material to which it will be bonded. The temperature around the Bearing Cartridge during operation ranges from ambient to -273°F The Bearing Cartridge material is Inconel 718 with a coefficient of expansion of 7.8 ppm/°F. Due to the low temperature extreme of the Bearing Cartridge, a nickel-chromium alloy foil gage with a self-temperature compensation (S-T-C) of 13 was specified. The S-T-C of 13 supplies the best fit of the apparent strain curve on Inconel 718 at the low temperature end of the HPOTP operating range. The alloy foil was also specified on a glass reinforced epoxy-phenolic resin backing since strains of less than 1% were to be encountered. The strain gage size was limited to what would fit the locations. With these considerations in mind, the strain gages called for use on the Bearing Cartridge were SK-13-031DE-350 and SK-13-031EC-350 by Micro Measurements. M-Bond 610 was designated as the bonding agent because of its outstanding job at cryogenic temperatures.

The strain gages were applied to the Bearing Cartridge as identified on Figure 10, curing the M-Bond 610 at 350°F for two hours and post-curing at 400°F for two hours. Figures 11, 12, 13 and 14 show the actual strain locations and wire routing. The strain gages and wires were then coated with Refset.

Transducer Calibration and HPOTP Assembly:

The instrumented Bearing Cartridge was ready for calibration and installation in the HPOTP. A bench calibration of the Bearing Cartridge was made on an Instron Machine using fixtures to simulate the HPOTP housing and bearing. Loads up to 5000 pounds were applied while deflection and strain measurements were made. The bench calibration was performed at ambient and liquid nitrogen temperatures. The strain verse load or deflection was then plotted. (Figure 15)

The Bearing Cartridge was then cleaned and installed in a HPOTP. The strain gage wires were routed out of the HPOTP through two Conax fittings (see Figure 7) After installation, the Bearing Cartridge calibration was checked by applying loads to the HPOTP's shaft and monitoring the strain gage output. This load application was performed at ambient and liquid nitrogen temperatures also.

HPOTP Engine Testing and Data Discussion:

After complete assembly, the instrumented HPOTP was shipped to the Santa Susana Field Laboratory of Rocketdyne for installation into an SSME. After installation, the deflection monitoring strain gages were checked for a "zero" reading. This verified that the HPOTP had been installed properly and the shaft was not already bottomed. A total of twenty-two "hot fire" tests were made with the instrumented HPOTP in an SSME. The test time varied from 1.5 to 200 seconds and included testing the HPOTP in three different SSMEs.

From the test data, plots of the HPOTP shaft travel and bearing load versus time were made. One test is depicted in Figure 16. At the start of the test the HPOTP is bottomed against the turbine end stop. After about 3 seconds into the test the shaft moves away from the stop and is axially balanced during changes in Engine power level. At cut-off, the shaft again bottoms against the turbine end stop. With the shaft moving on and off the stops, a verification of the strain gage calibration was made.

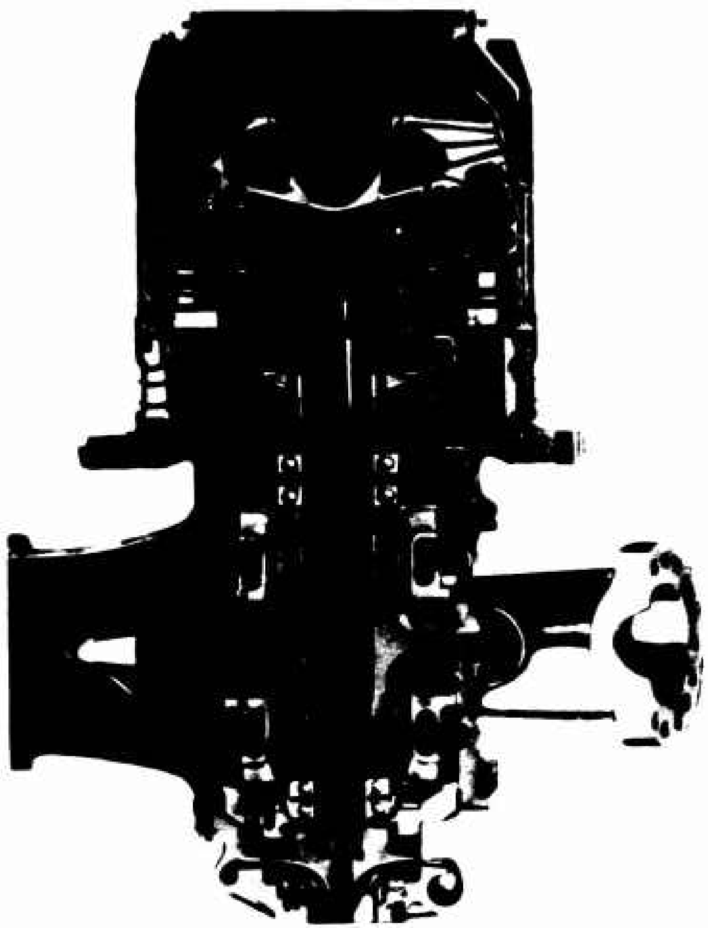
Figure 17 depicts bearing load and shaft position as monitored by the instrumented Bearing Cartridge. At engine start, the HPOTP shaft is again bottomed against the turbine end stop. Load can be noted being applied to the bearings of up to 2000 pounds. After leaving to stop, the shaft is again balanced axially and the load monitoring channel is essentially zero. At cut-off, the shaft bottoms on the turbine end stop and a large load of about 6000 pounds is applied to the bearings. After four seconds, the shaft moves to the pump end stop and another load is applied to over 4000 pounds on the bearings.

As the engine test data was reviewed from the instrumented HPOTP, insight was gained and corrective action was taken to lower HPOTP bearing loads. By lowering the bearing loads the life of the bearings was increased. After a small engine cut-off valve sequence change, the loads to the bearing were cut to below 1000 pounds. Other changes were made to insure that the bearing loads in the HPOTP remain low.

Designing, building and using the instrumented Bearing Cartridge provided the needed data to insure proper bearing life in the HPOTP. This type of testing insures the SSME will meet the expected design life required by the Space Shuttle Program.

figure 1

HIGH PRESSURE OXYGEN TURBOPUMP



KEY PERFORMANCE PARAMETERS	RPL		FPL	
	MAIN	BOOST	MAIN	BOOST
PUMP INLET FLOWRATE (LB/SEC)	1067.1	108.7	1158.8	124.3
PUMP INLET PRESS.(PSIA)	405.2	4146.1	423.0	4635.6
PUMP DISCHARGE PR (PSIA)	4283.7	7329.4	4782.5	8116.3
PUMP EFFICIENCY	0.678	0.807	0.675	0.809
TURBINE FLOWRATE (LB/SEC)	62.1		69.6	
TURBINE INLET PR (PSIA)	4969.9		5553.0	
TURBINE INLET TEMP (DEG R)	1399.2		1467.6	
TURBINE PRESS RATIO	1.495		1.523	
TURBINE EFFICIENCY	0.812		0.828	
TURBINE SPEED (RPM)	27885		29861	
TURBINE HORSEPOWER	23950		29410	

figure 2

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INSTRUMENTED HPOTP BEARING CARTRIDGE

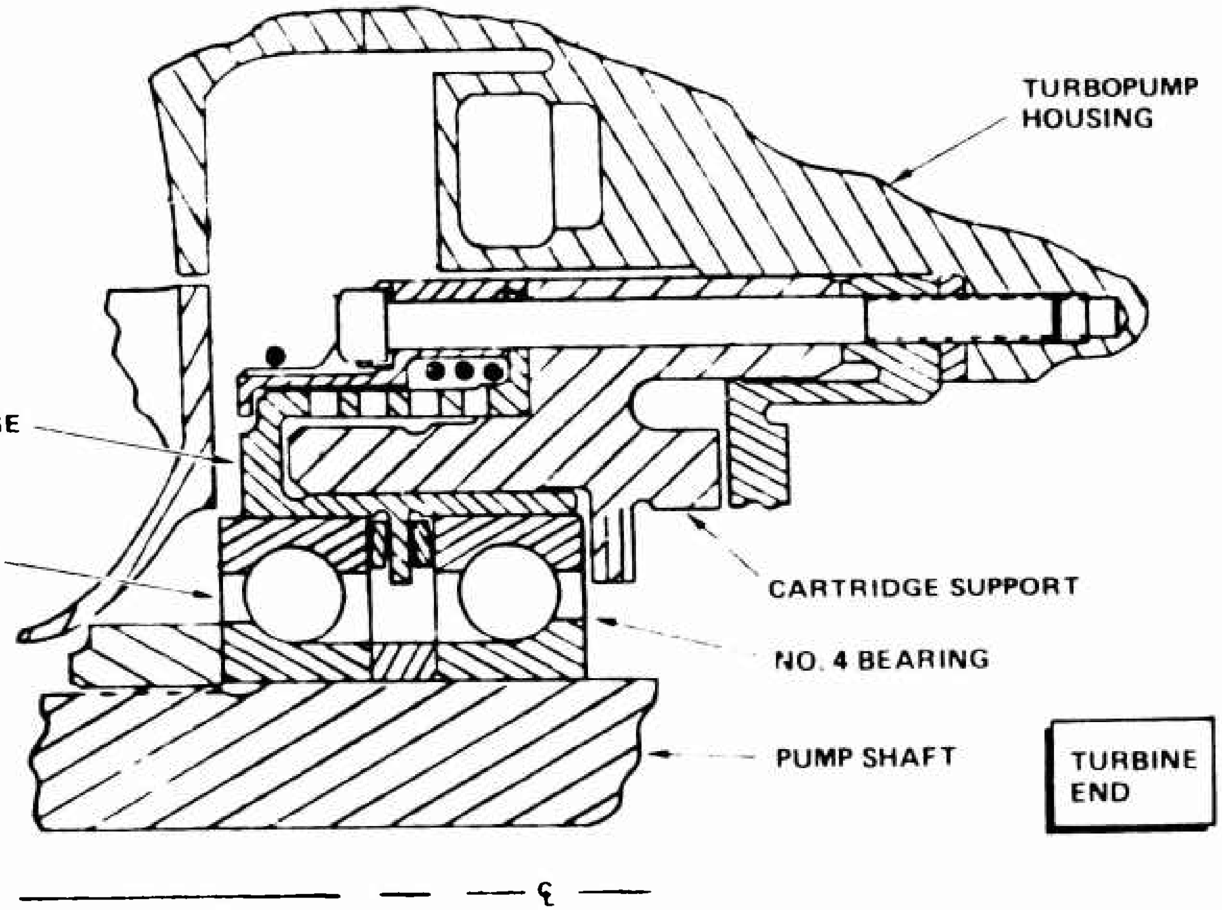

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figure 3

INSTRUMENTED HPOTP BEARING CARTRIDGE

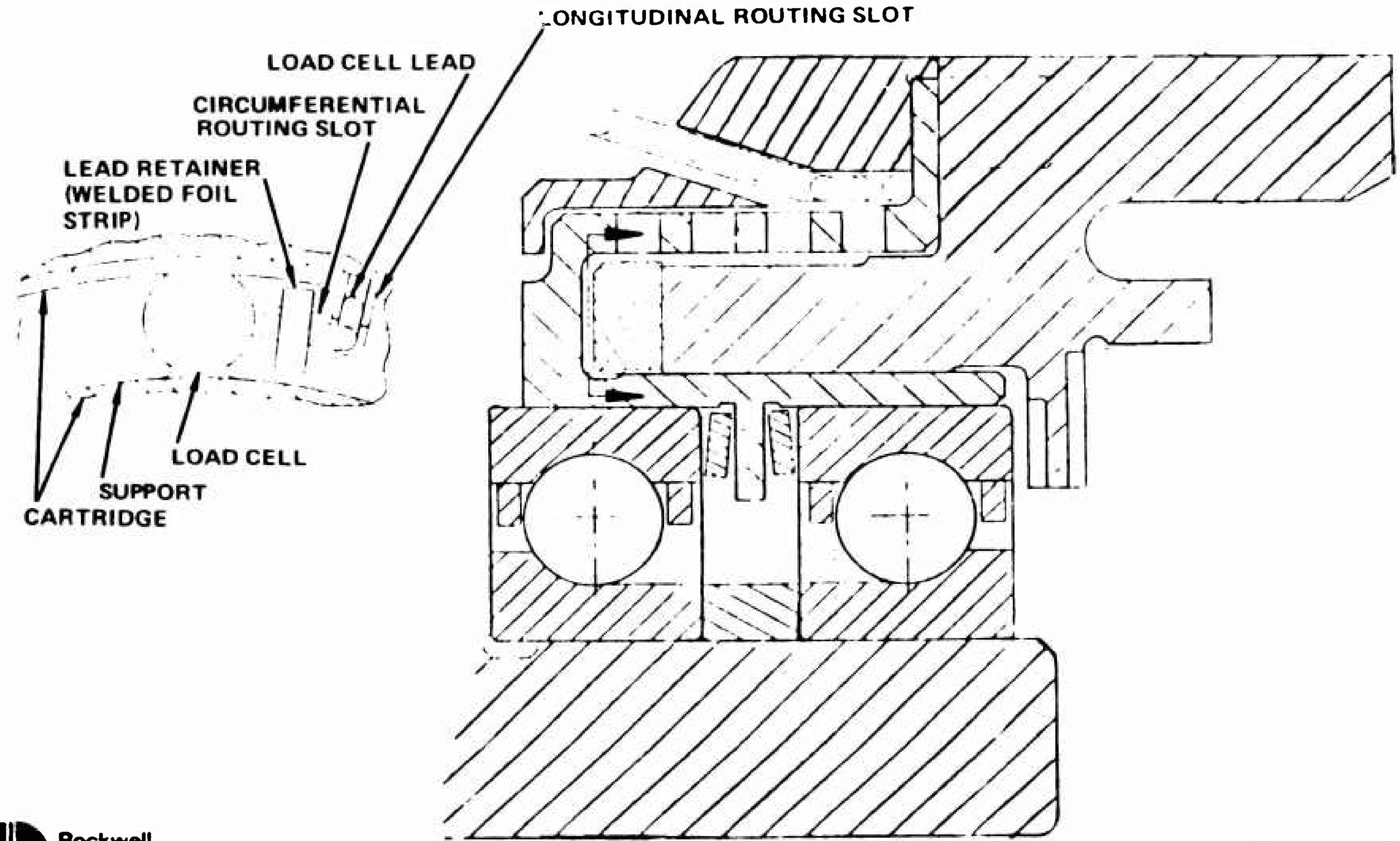

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figure 4

INSTRUMENTED HPOTP BEARING CARTRIDGE PROPOSED STRAIN GAGE LOCATIONS

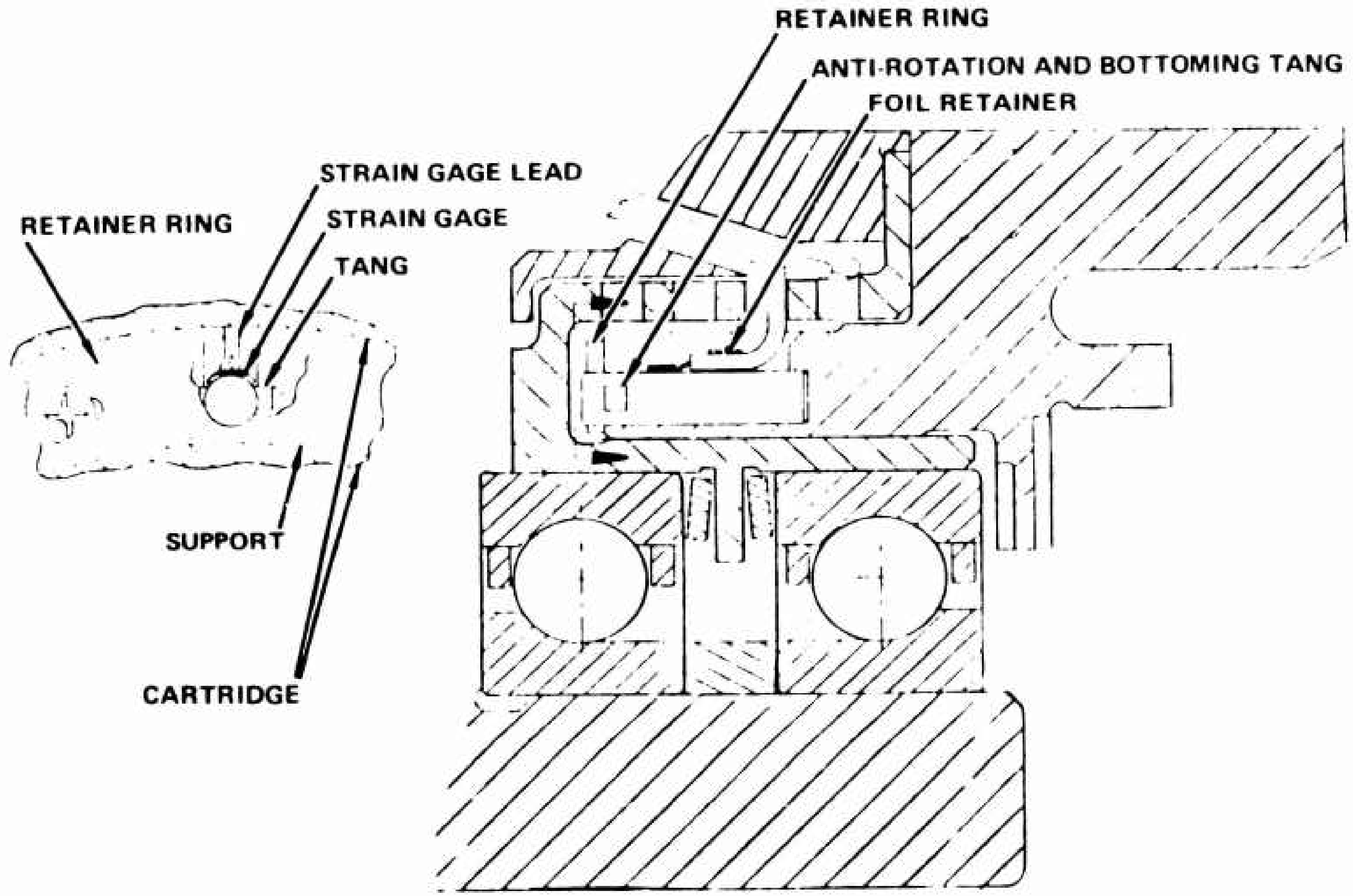

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figure 5

INSTRUMENTED HPOTP BEARING CARTRIDGE

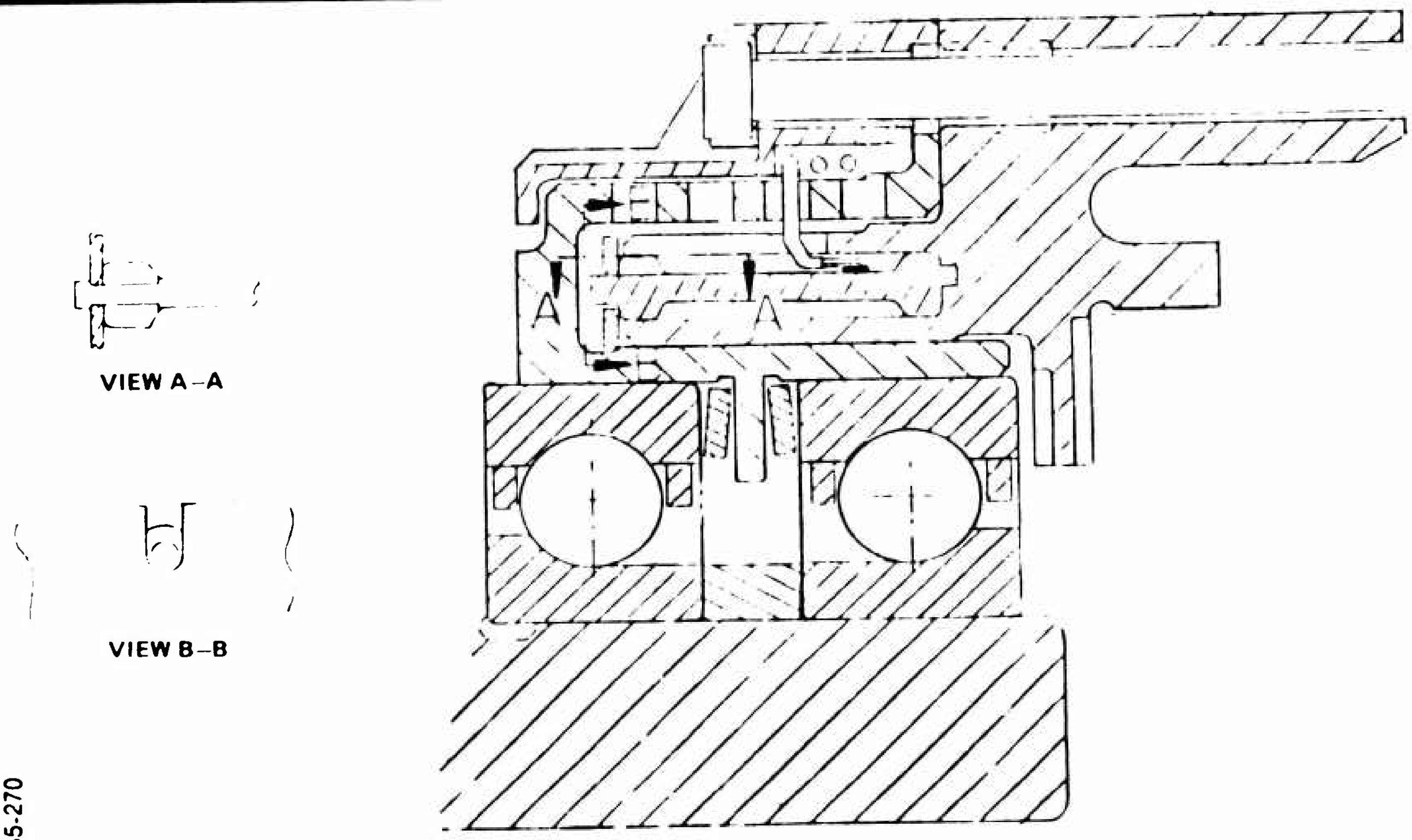

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figure 6

INSTRUMENTED HPOTP BEARING CARTRIDGE PROPOSED STRAIN GAGE LOCATIONS

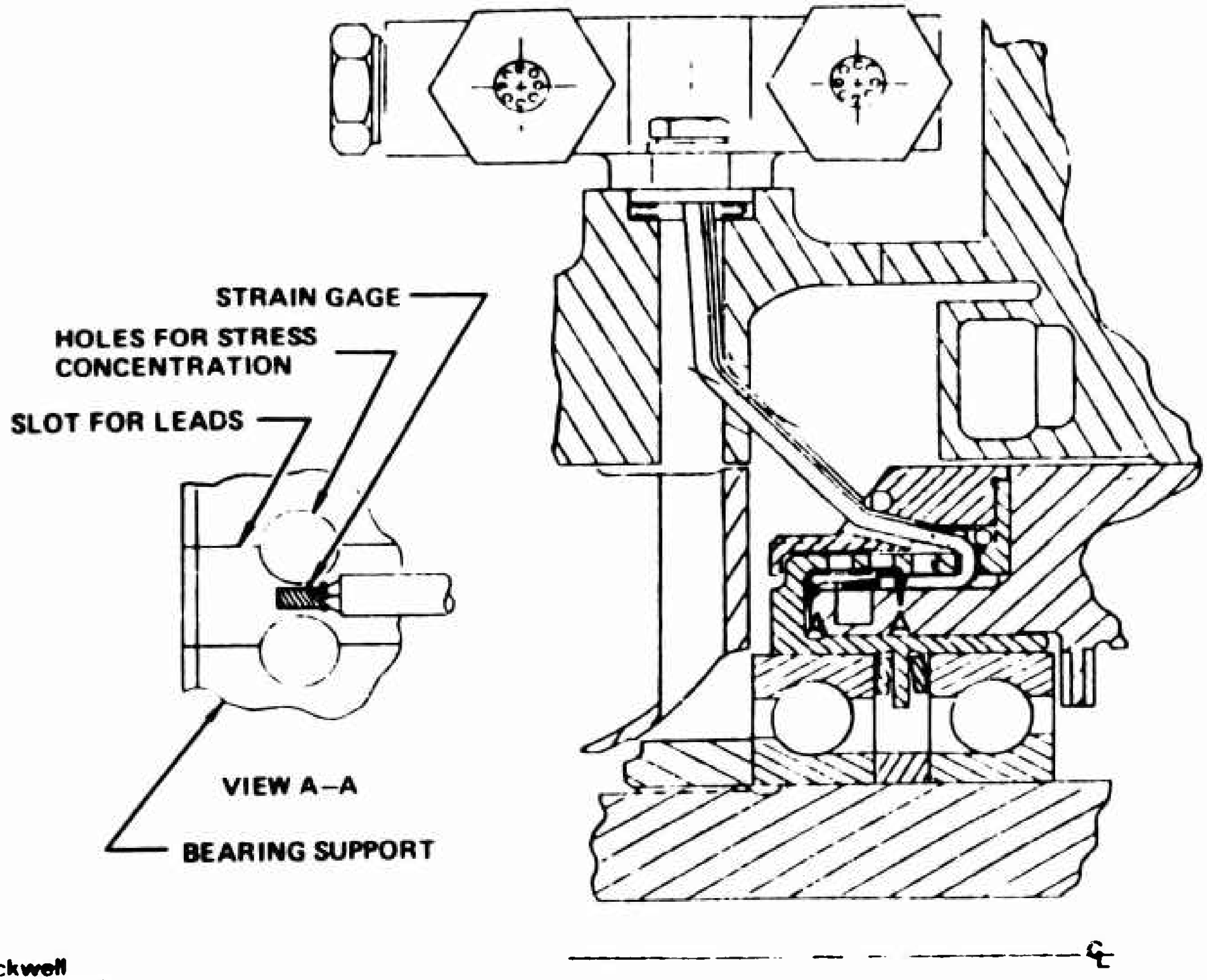

figure 7

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INSTRUMENTED HPOTP BEARING CARTRIDGE
PROPOSED STRAIN GAGE LOCATIONS

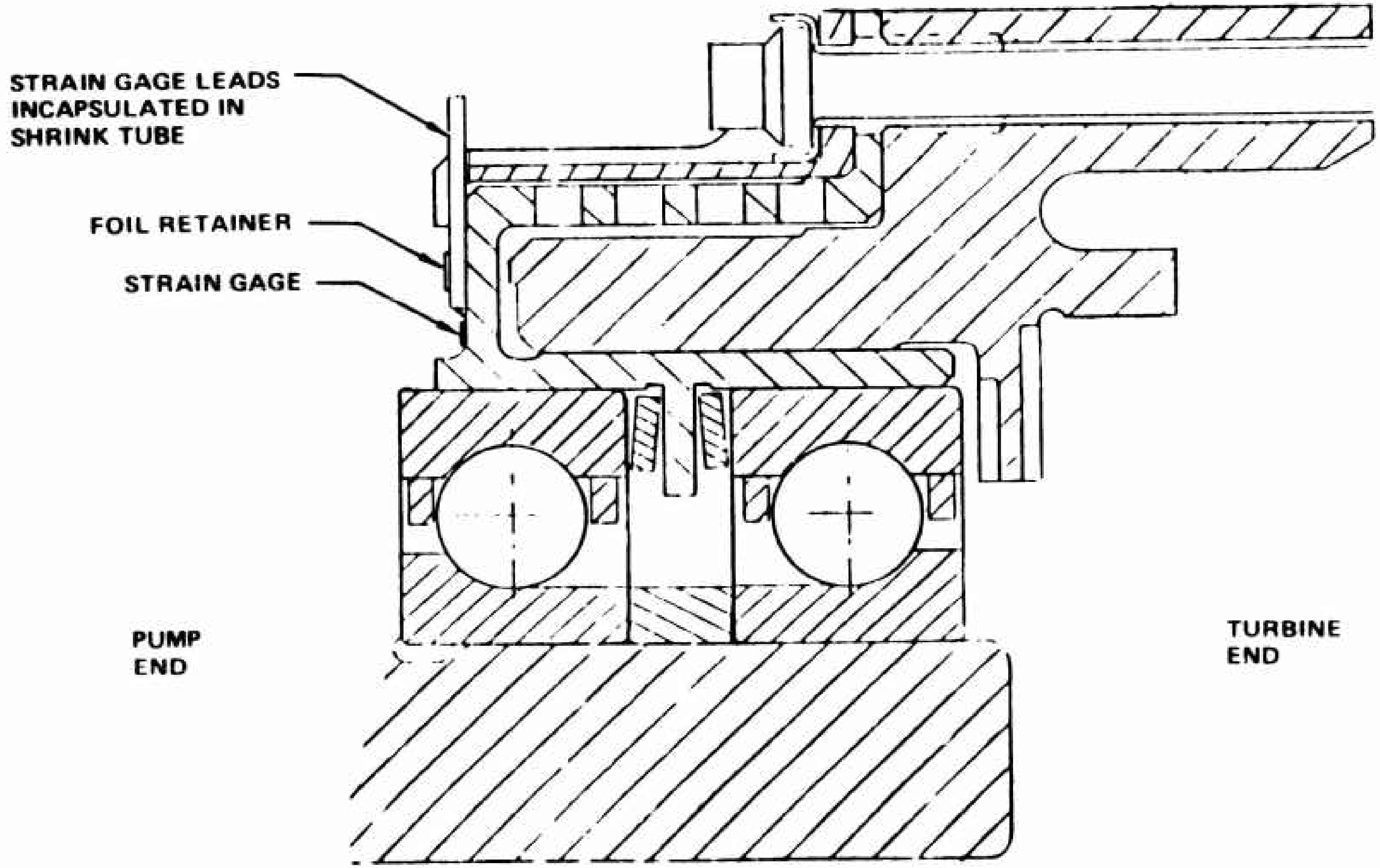

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figure 8

INSTRUMENTED HPOTP BEARING CARTRIDGE PROPOSED STRAIN GAGE LOCATIONS

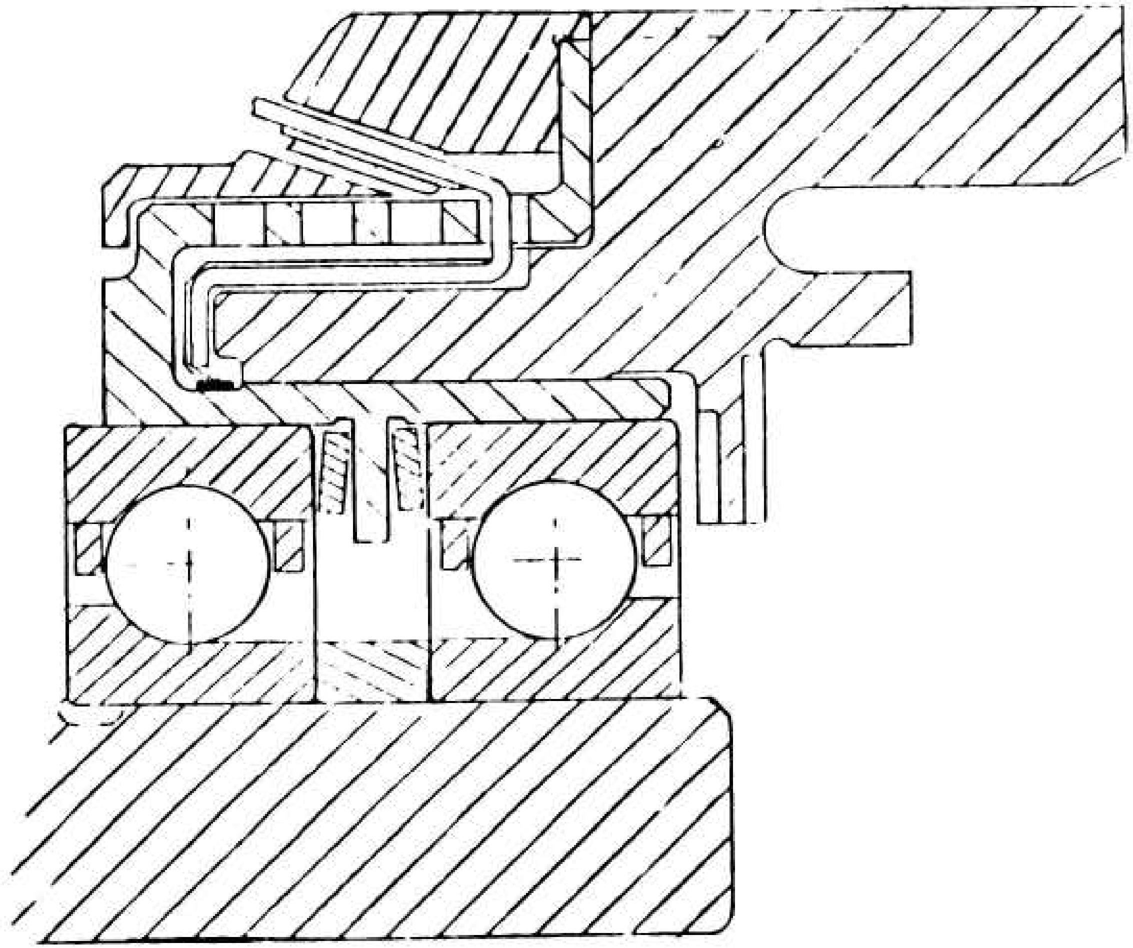

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figure 9

INSTRUMENTED HPOTP BEARING CARTRIDGE STRAIN GAGE INSTALLATION

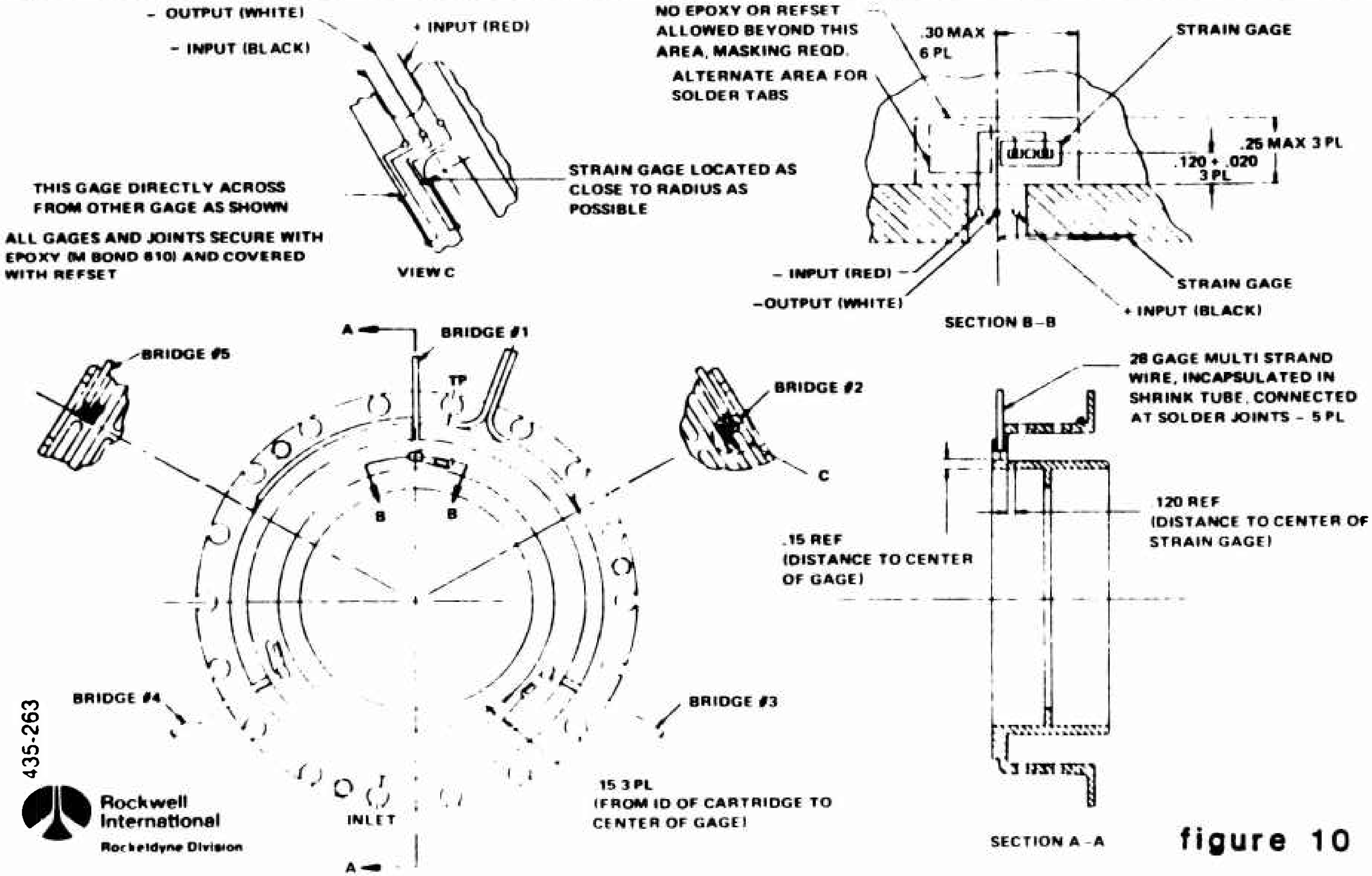

figure 10

HPOTP BEARING CARTRIDGE

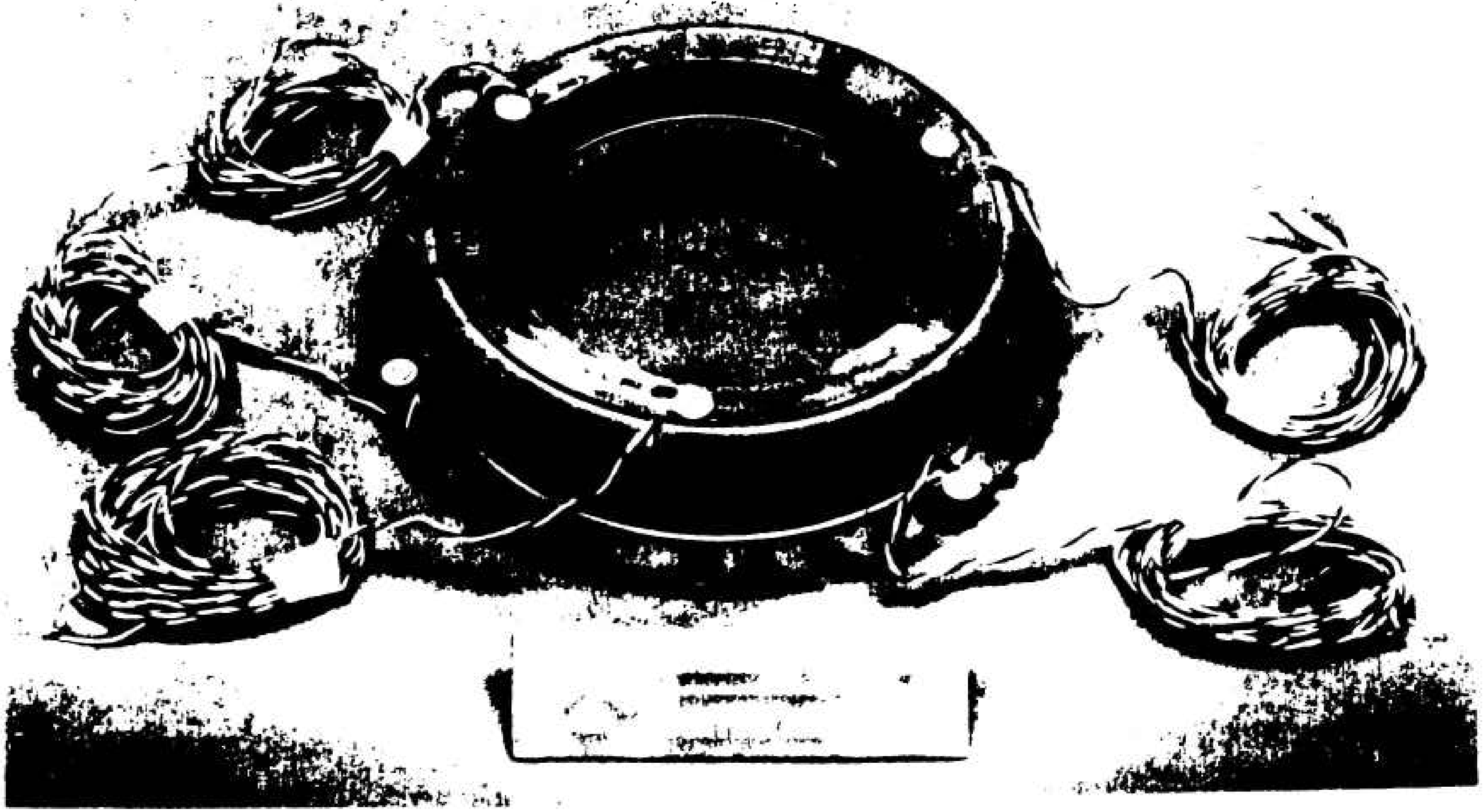

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figure 11

HPOTP BEARING CARTRIDGE

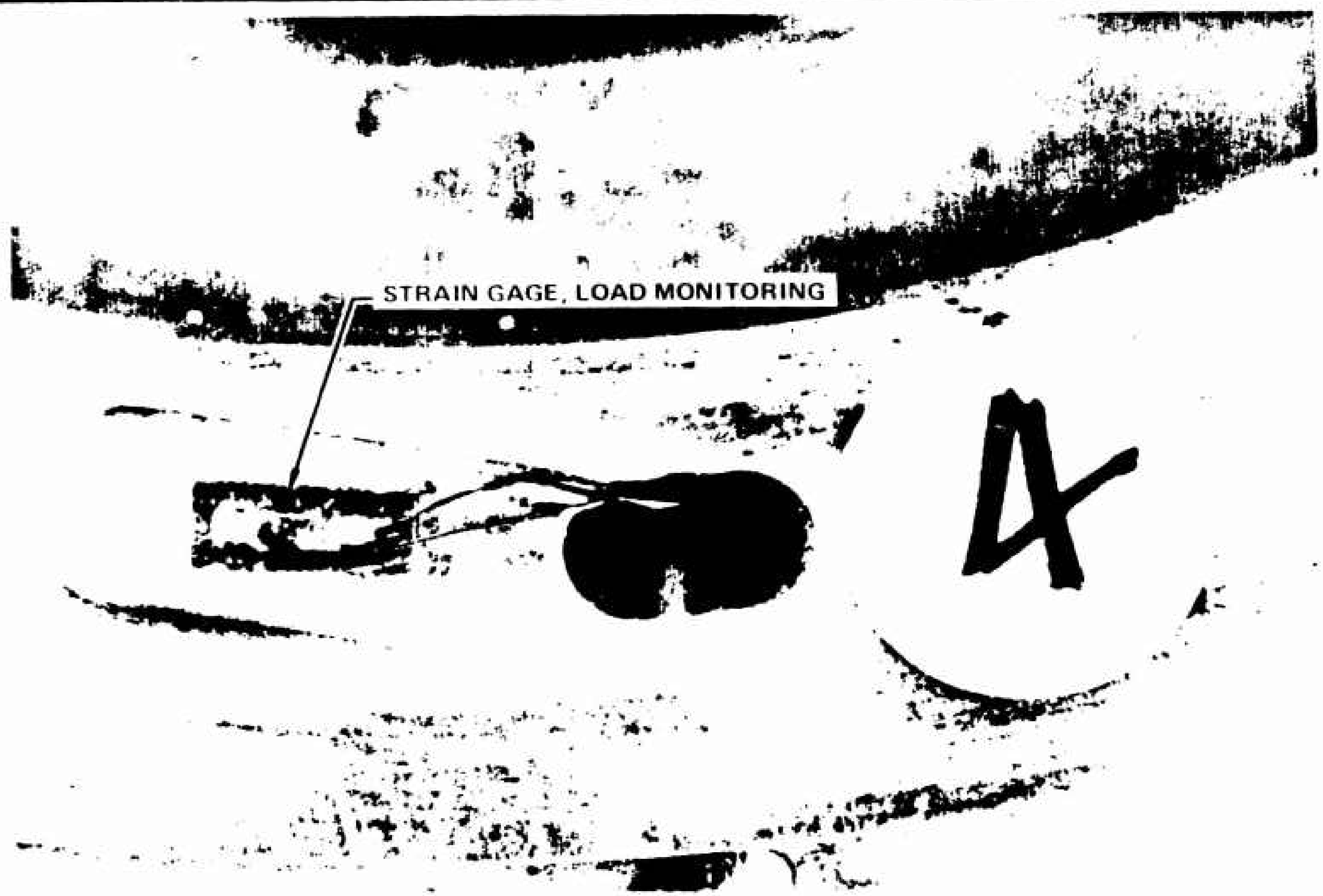

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figure 12

HPOTP BEARING CARTRIDGE

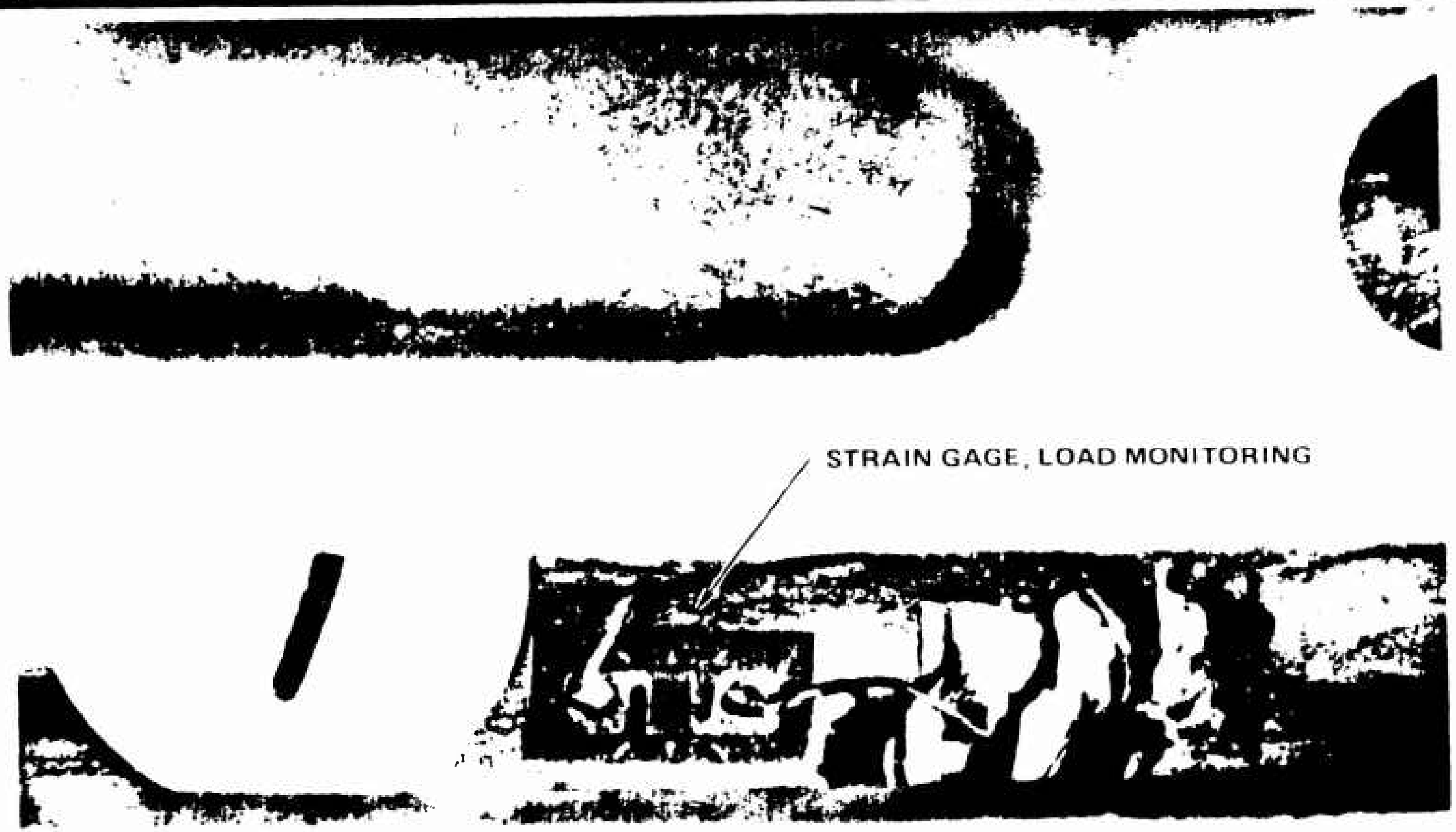

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figure 13

HPOTP BEARING CARTRIDGE

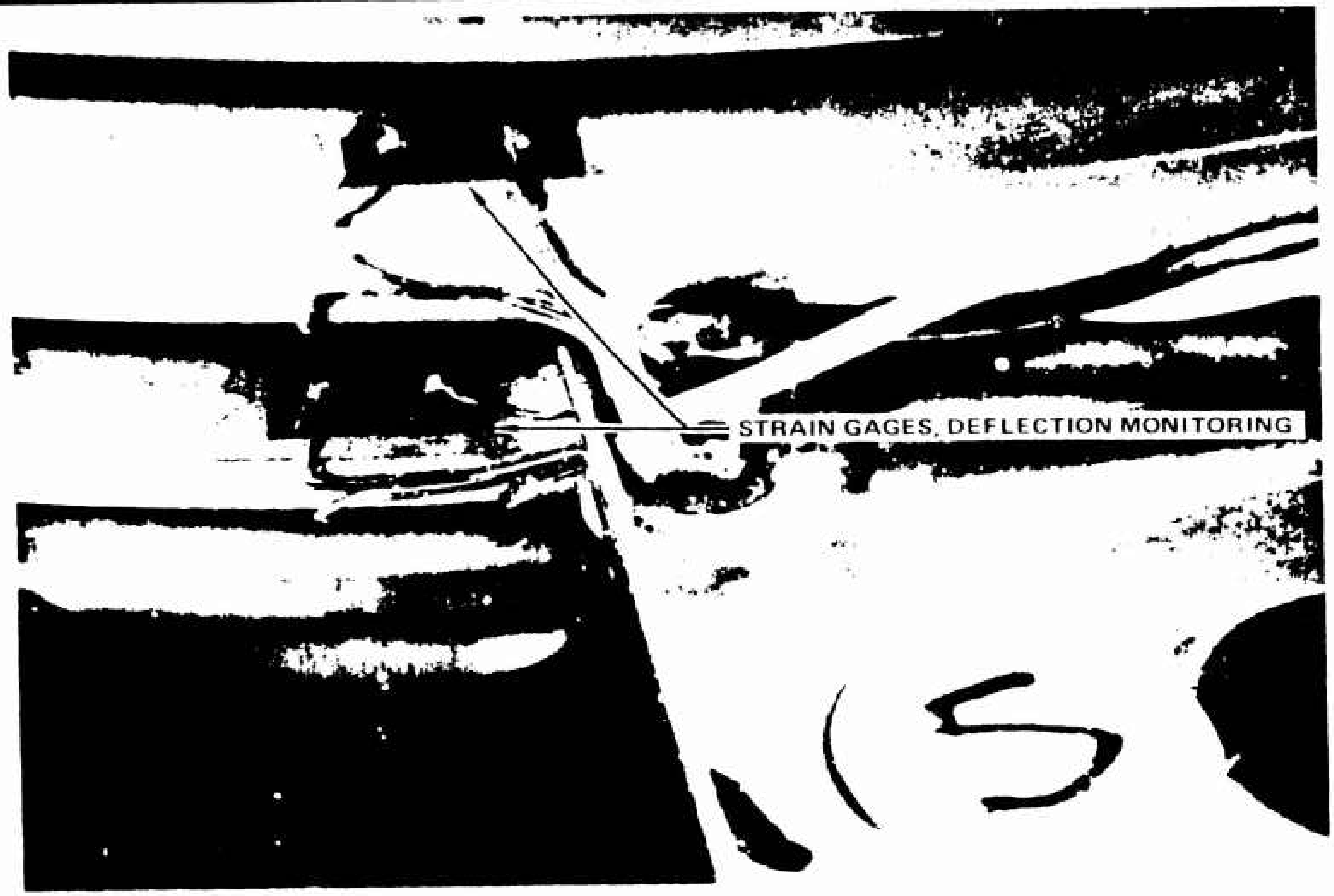

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figure 14

INSTRUMENTATED HPOTP BEARING CARTRIDGE CALIBRATION

STRAIN vs DEFLECTION OF TE CARTRIDGE GAGE 2 (BENCH TEST)

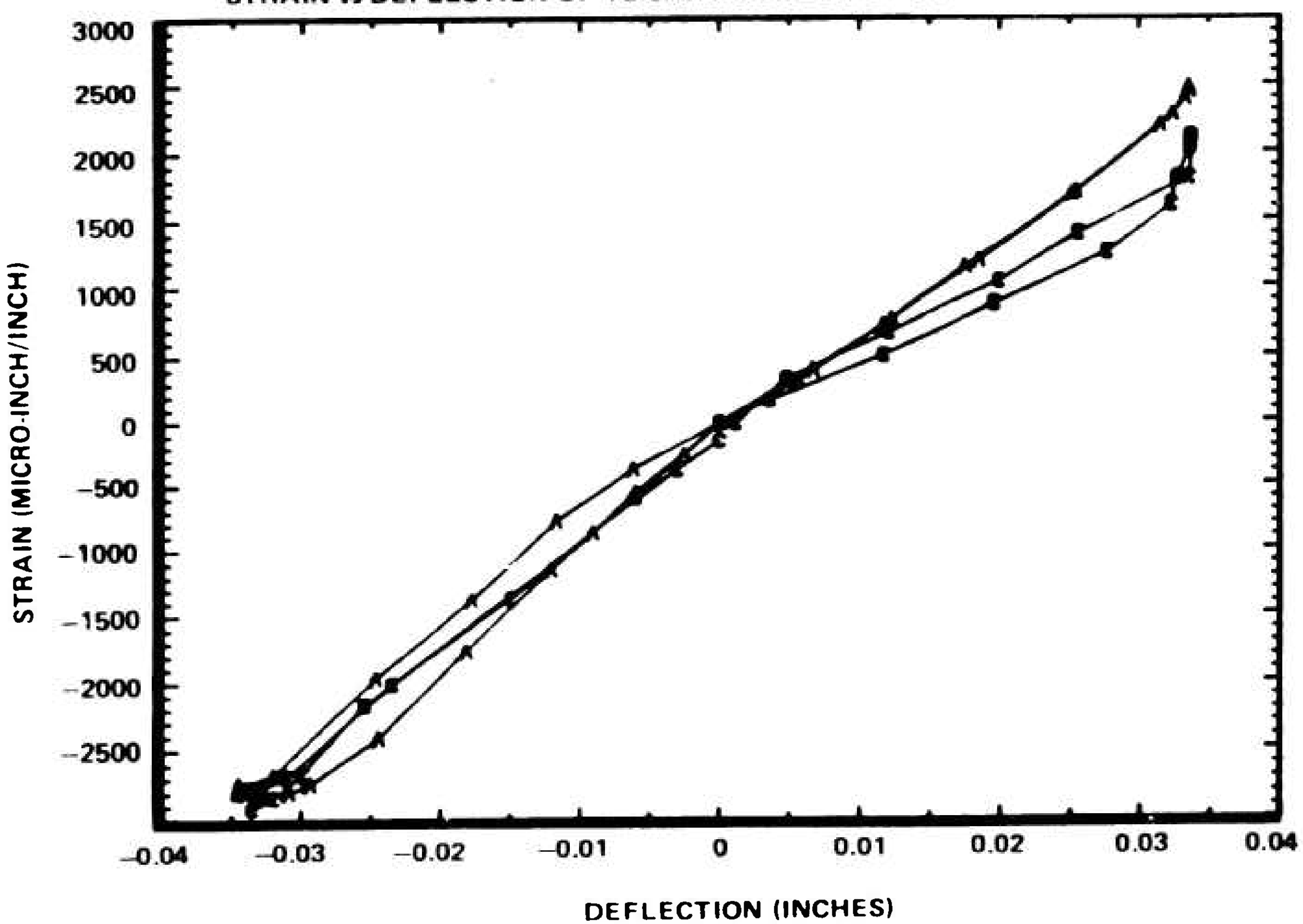

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figure 15

INSTRUMENTED HPOTP BEARING CARTRIDGE SSME ENGINE TEST

TEST 750-103 SHAFT DEFLECTION OF HPOTP ENTIRE TEST (CAGE 1)

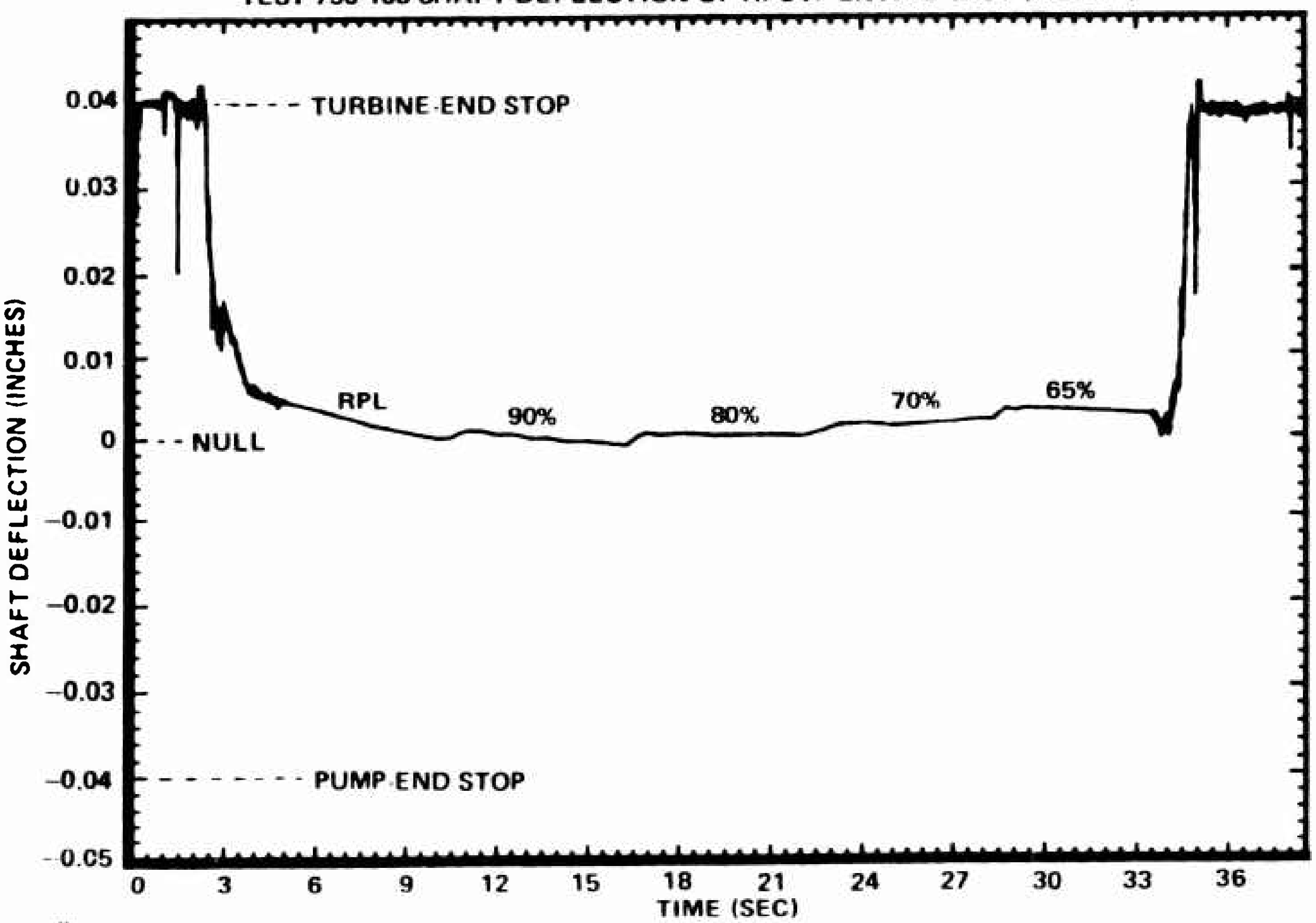

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figure 16

INSTRUMENTED HPOTP BEARING CARTRIDGE SSME ENGINE TEST

figure 17

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